Development and Testing of the Tropospheric Trace Species Sensing FPI Prototype

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***Abstract*—The Tropospheric Trace Species Sensing Fabry-Perot Interferometer (TTSS-FPI) is a NASA Instrument Incubator Program (IIP) project for risk mitigation of enabling concepts and technology applicable to future Science Mission Directorate (SMD) atmospheric chemistry measurements. While the desired implementation for future science missions is a geostationary-based measurement of tropospheric ozone and other trace species, an airborne sensor has been developed within IIP to demonstrate the instrument concept and enabling technologies that are also applicable to space-based configurations. The concept is centered about an imaging Fabry-Perot interferometer (FPI) observing a narrow spectral interval within the strong 9.6 micron ozone infrared band with a spectral resolution ~0.07 cm^{-1}. This concept is also applicable to and could simplify designs associated with atmospheric chemistry sensors targeting other trace species (which typically require spectral resolutions in the range of 0.01 - 0.1 cm^{-1}), since such an FPI approach could be implemented for those spectral bands requiring the highest spectral resolution and thus simplify overall design complexity. The measurement and instrument concepts, enabling technologies, approach followed for development and demonstration within IIP, and a summary of progress-to-date will all be reported; emphasis will be placed on recent laboratory testing and characterization results.**

I. INTRODUCTION

Measurement of tropospheric chemistry is identified as one of the key areas to be included in Earth science missions of the 21st century in the NASA Science Mission Directorate (SMD) Strategic Enterprise and Science Research Plans. While many species are fundamental to enabling atmospheric chemical processes, ozone is clearly recognized as one of the most important gas phase trace constituents in the troposphere. Its importance stems from four main reasons: 1) ozone is a key oxidant in tropospheric photochemistry; ozone photolysis is one of the principal sources of the hydroxyl radical (OH), which is the most important radical species associated with the photochemical degradation of anthropogenic and biogenic hydrocarbons; 2) exposure to enhanced levels of tropospheric ozone [1]-[2] negatively impacts health, crops, and vegetation; ozone is responsible for acute and chronic health problems in humans and contributes toward destruction of plant and animal populations; 3) as a greenhouse gas it contributes toward radiative forcing and climate change; and 4) levels have been increasing and will continue to do so as concentrations of precursor gases (oxides of nitrogen, methane, and other hydrocarbons) necessary for the photochemical formation of tropospheric O_3 continue to rise. Space-based detection of tropospheric ozone is critical for enhancing scientific understanding and lessening impacts of exposure to elevated concentrations. Such a global measurement capability is needed since ozone is spatially heterogeneous (due to non-uniform sources/sinks and transport) and high levels are not unique to urban areas, as is evidenced by enhanced tropospheric O_3 being observed over the south tropical Atlantic Ocean. The objective of the Tropospheric Trace Species Sensing Fabry-Perot Interferometer (TTSS-FPI) within NASA's Instrument Incubator Program (IIP) was to develop and demonstrate a prototype sensor for further risk mitigation of an advanced atmospheric remote sensor intended for geostationary-based measurement of tropospheric ozone and other trace species, which fits directly within the SMD Atmospheric Ozone and chemistry measurement themes.

II. Technical Approach

Observations of tropospheric trace species face two fundamental challenges: 1) the need for sufficient spatial resolution to identify the spatial distribution inhomogeneities of constituents that result from non-uniform sources/sinks and atmospheric transport, and 2) the need for adequate temporal resolution to resolve daytime and diurnal variations. Both of these requirements are ideally fulfilled by observation from geostationary orbit. While differential absorption lidar and other active sounding systems operating from low Earth orbit could permit high vertical resolution, they would only provide relatively sparse horizontal spatial sampling. The Tropospheric Emission Spectrometer (TES) instrument on the EOS-Aura satellite is providing the first global data set on distribution of tropospheric ozone. However, the EOS Request for Information panel has recommended technology development to achieve higher horizontal resolution than is possible with the EOS-AURA payload [3]-[4]. This would address the key tropospheric ozone process-related questions that are expected to remain in the post-AURA time period.

Earlier NASA-sponsored research [5] has shown that a tropospheric ozone measurement capability can be achieved using a satellite-based nadir-viewing device making high spectral resolution measurements with high signal-to-noise ratios, and that a Fabry-Perot interferometer (FPI) is quite suitable for this task. Implementation in the infrared portion of the spectrum utilizes the strong 9.6 micron ozone band and yields continuous day/night coverage independent of solar zenith angle. Using an FPI affords high optical throughput while operating at high spectral resolution, and has a proven success record in previous applications. The same technology being advanced for TTSS-FPI is applicable to measurements of other trace species, and could greatly simplify other atmospheric chemistry sensor designs (which typically require spectral resolutions in the range of 0.01 - 0.1 cm-1) by implementing this approach for spectral bands requiring the highest spectral resolution in those applications and thus simplify overall design complexity

A. Measurement Concept

Molecular collisions during the absorption/emission process give rise to collisional or pressure broadening, and the corresponding profile function can be represented by the Lorentz line shape. The Lorentz half-width is proportional to pressure and is approximately inversely proportional to the square root of temperature. The other significant mechanism for broadening in the terrestrial atmosphere is Doppler broadening, which originates from a Doppler shift in the frequency of radiation associated with the absorption/emission feature due to thermal motion of the radiating molecules. Unlike the Lorentzian half-width, the Doppler half-width does not have a pressure dependence and therefore its change with altitude is due to temperature alone. The Voigt profile is formed from the convolution of two independent broadening formulas (i.e., Lorentzian and Doppler), and describes the spectral line broadening as a function of atmospheric altitude. In the high or low pressure limits, the Voigt profile approaches the Lorentz or Doppler profiles, respectively, which explains the basis for this measurement concept: tropospheric information content in the measured signals can be maximized by spectrally isolating wings of strong ozone lines, since wings of strong lines are due primarily to pressure broadening in the troposphere.

B. Instrument Concept

The TTSS-FPI instrument concept employs a double-etalon FPI to achieve the necessary high-resolution (0.068 cm^{-1}), narrow-band infrared emission measurements within the strong 9.6-micron ozone band. This implementation requires a single-order transmission function, rather than the periodic nature of the standard Fabry-Perot instrument bandpass (which can be advantageous when observation of periodic spectra is desired). This is achieved using additional optical elements (specifically, a low resolution etalon, LRE, a high resolution etalon, HRE, and an ultra-narrow bandpass filter all arranged in a series configuration) to reduce the effect of unwanted passbands, improve sideband rejection, and extend the effective free spectral range. Larar et al. [6] describe such a system for a cross-track spatially scanning non-imaging instrument configuration. The system being advanced herein incorporates an advanced focal plane array (FPA) detector to perform spatial imaging, and spectral tuning is accomplished through precise mechanical scanning of etalon plate gaps; Larar et al. [7] describe such a system for geostationary implementation.

C. Enabling Subsystems & Technologies

The instrument system is an imaging Fabry-Perot interferometer (FPI) based on a tunable double etalon designed to collect high resolution (resolving power ~ 15000) spectra of the Earth/atmosphere in the 9.6 micron ozone band over an infrared FPA. Spectral information is acquired by taking a series of images at different FPI plate separation distances. As the FPI is scanned, each pixel measures a signal that represents the convolution of the instrument transfer function with the spectrum incident at that pixel location. For each plate separation setting, slight differences in effective center wavelength occur as a function of exact pixel location, because the surfaces of equal phase difference are curved, not flat like the focal plane array. Thus the FPI needs to be scanned beyond the spectral range required for center pixel to ensure all spatial elements in the three-dimensional spatial-spectral data set have complete spectral coverage. To enable the spectrally tunable imaging FPI measurement technique for TTSS-FPI, for achieving high-resolution over narrow spectral ranges, three enabling technologies have been demonstrated within NASA's IIP: precision control of etalon plates to demonstrate accurate spectral tuning and parallelism control of the LRE and HRE; high-sensitivity two-dimensional infrared detector arrays to demonstrate the required SNR and imaging configuration; and spectral and radiometric calibration, to demonstrate spectral registration and absolute intensity fidelity in radiance measurements.

D. IIP Implementation Approach

The next logical step in advancing and validating this measurement technique is performing atmospheric measurements from a more realistic configuration (i.e. making nadir-viewing emission observations). This would address several critical operational challenges associated with this measurement; most importantly, signal impact from background (surface) variability of temperature, emissivity, and topography. Within IIP we have developed and demonstrated an integrated instrument system from laboratory testing to provide technique validation, demonstration of enabling components within an integrated system, and the utility of the imaging technique. Subsequent atmospheric test flights will be a crucial risk-mitigating activity for the eventual spaceflight instrument by validating enabling technologies and providing additional measurement concept verification, along with evaluating FPA small/large format tradeoffs, and autonomous operation, all from a more relevant environment than possible from the ground. Re-baseline of the TTSS-FPI program became necessary during August, 2004 to bring satisfaction of technical objectives within closer reach; specifically, this was achieved by eliminating the airborne flight demonstration task from the TTSS-FPI IIP program plan. Alternatively, the program plan was modified to perform more extensive lab-based testing and characterization at system-level (spectral, spatial, & radiometric) to still satisfy the program technical objectives of demonstrating an imaging Fabry-Perot interferometer: spectral tuning, spatial imaging, and radiometric & spectral calibration, independent of a flight opportunity. In addition, other field demonstration opportunities are being pursued now that the IIP tasks have been completed. This includes maintaining readiness for a future piggyback flight of opportunity, as well as to consider possible ground-based, high-altitude deployments which could provide near-simultaneous viewing of a polluted/clean atmosphere and, possibly, a water/land coastline interface. This approach was not intended to replace a flight opportunity but, rather, enable an additional demonstration path independent of project-external constraints. The TTSS-FPI program plan revision still included the task of performing a spaceflight sensor concept study using the best characterization and performance data available at the time, with the intent to infuse field-phase data as they are obtained.

III. System Development Status

The TTSS-FPI instrument system-level integration has been performed but, as of this writing, not completely optimized. While the entire system-level instrument integration has been performed, it was done primarily as a fit-check for components and assemblies as well as for verification of system-level logistics. More work is needed on the etalon assembly gap adjustment unit to enable cryogenic adjustment of initial alignment after cool-down, since the first set of motors did not have sufficient torque. Complete system-level optimization and performance characterization awaits modification of the etalon assembly gap adjustment unit, and is currently underway. Meanwhile, extensive characterization testing has been performed in both the ambient bench and cryogenic dewar environments. Subsystem-level characterization performed in the ambient bench environment served to demonstrate and characterize etalon control and spectral tuning, and etalon spectral response using blackbody, laser, and solar targets. Near system-level testing and characterization performed in the cryogenic dewar environment demonstrated key attributes for this imaging FPI including, for example, spatial imaging, radiometric response, and spectral tuning at the near system-level (i.e. containing the HRE in the etalon assembly) using blackbody, laser, solar, and miscellaneous lab targets.

Spatial imaging fidelity has been demonstrated in the cryogenic dewar environment by FPA-inferred spatial sizes matching known-target dimensions. Such performance demonstrations were performed during both sun-look and hallway lab target tests. Radiometric calibration methodology fidelity has been demonstrated in the cryogenic dewar environment by using cold, thermally-stable FPA measurements of known target temperatures to show radiometric calibration transforms measurements to expected scene temperatures with greatly reduced pixel-variance over uniform scenes. Such performance demonstrations were performed during both calibration target and hallway lab target tests. Spectral tuning fidelity has been demonstrated in the ambient lab and cryogenic dewar environments by being able to precisely repeat desired spectral measurements via etalon gap control. Such performance demonstrations were performed during bench-level sun-look and capacitance repeatability tests and dewar-based PZT scan tests. These results are discussed in detail within the Laboratory Testing and Data Analysis section of the TTSS-FPI Final Report [8].

III. Laboratory Testing & Key Demonstration Results

During the last phase of the TTSS-FPI IIP program, some very significant demonstration results were achieved. Specifically, spectral-tuning-induced fringes were recorded which demonstrated achievement of an imaging FPI, and the repeatability of capacitance-based measurements were realized which demonstrated the desired spectral fidelity feature for this instrument system. Achieving cryogenic motor control for the etalon gap adjustment unit, which is needed for initial etalon alignment and for placement within the capacitance control range, will occur in the post-IIP activities currently ongoing. Such motor control along with view of an "extended source" will yield the more familiar and desired fringe pattern characteristics. Subsequently, the capacitance repeatability characteristic will be exploited to obtain spectral calibration for aligned etalon positions throughout the spectral scan range. As mentioned earlier, the instrument system fidelity for spatial imaging, radiometric calibration methodology, and spectral tuning has been demonstrated in the ambient lab and cryogenic dewar testing program. This subsystem- and pseudo-system-level (i.e. w/ HRE) in dewar testing has demonstrated several project enabling technical objectives: Etalon control & spectral fidelity at room and cryogenic temperatures, encouraging radiometric calibration with FPA temperatures at and below 77K, imaging fidelity at nominal system cryogenic temperatures and, most importantly, an imaging FPI in the dewar cryogenic environment.

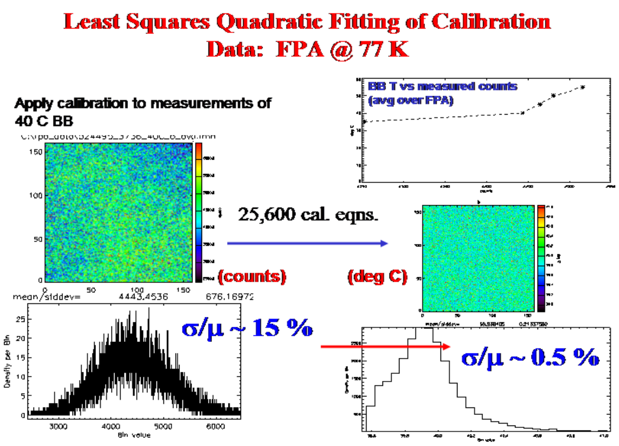

Figure 1. Radiometric calibration approach applied to test data.

Figure 1 illustrates the impact of applying calibration equations derived for each of the 25,600 detector pixels to an independent 40 C blackbody scene. The image and histogram at left show the original as-measured-counts scene variance and on the right shows the corresponding products after application of pixel calibrations. Two significant observations are immediately obvious: 1) the scene variance drastically decreased from a standard deviation to mean ratio of 15 % to 0.5 % after application of calibration equations; and 2) the calibrated scene has a mean of 39.94 C with standard deviation of 0.21 C. This result demonstrates excellent radiometric calibration potential of this system, especially after considering that such performance will only improve for colder (i.e. more optimal) FPA temperatures.

Sunlook tests were done during the August-September, 2005 timeframe with the FPA cooled to ~ 38 K inside our IR Labs instrument dewar. Figure 2 summarizes the results showing sample images from tests performed on 9/14/05. The top row images correspond to actual measured scenes, whereas the bottom row was created with simulations that best match the measured scenes in an RSS sense. Rotated elliptical Gaussian shapes were needed to best match the measurements; this is because of a known issue of image stretching and ghosting resulting from the dewar window not being properly Anti-Reflection (AR) coated (as specified, but not procured). Nonetheless, the results are quite impressive. The goal here is to see how accurately the solar disk diameter can be inferred from system images. The "truth" = 23.48 pixels is calculated based upon Earth-sun distance, solar disk diameter, and instrument field-of-view specifications. The mean of all measurements (from tests on 8/17/05 and 9/14/05) is a sun diameter of 23.18 pixels, or ~ -1.3% below "truth." The results change with atmospheric conditions (e.g. cirrus) along the optical path, and we know some measurements contain significant contamination; for example, some of these tests were performed during apparent "clear holes" on the day hurricane Ophelia was approaching LaRC. Correspondingly, considering the subset of "good" tests yields a sun diameter of 23.475 pixels, or ~ -0.02% below "truth" (with a standard deviation of +/- 0.41%).

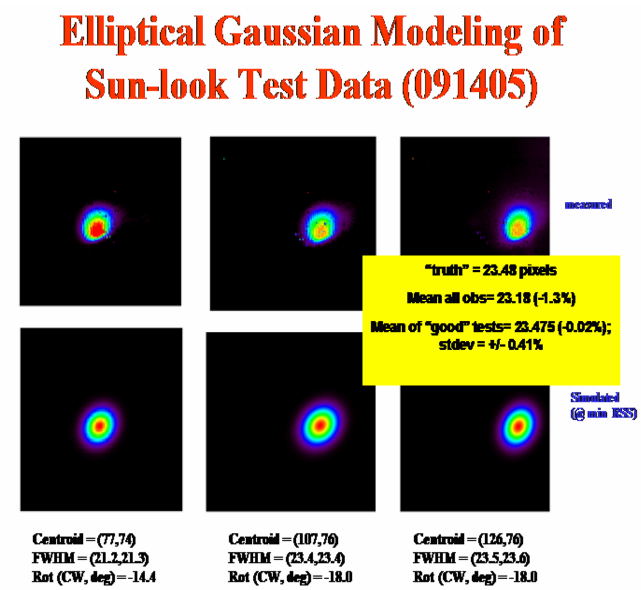

Figure 2. Spatial imaging performance demonstrated with sun-look test data.

Figure 3 shows a comparison of radiance reaching and through the sensor from simulation versus effective measurements from the FTIR/HRE sunlook observations. The HRE "effective measurements" are formed by numerically integrating the FTIR observations across the HRE bandpass as the etalon is spectrally-tuned. The agreement between measurement and simulation shown in Figure 3 is excellent considering the uncertainty in atmospheric state and exact etalon spectral positioning during the PZT voltage scan.

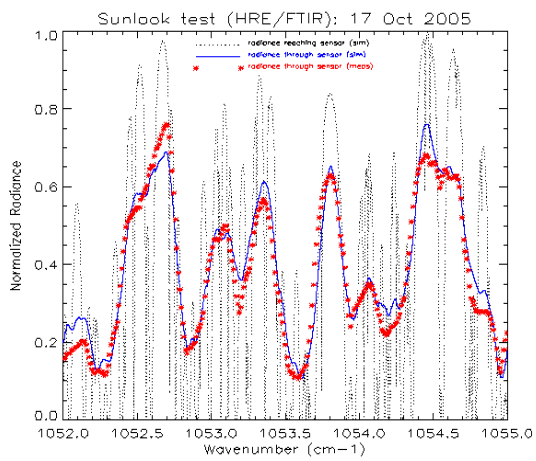

Figure 3. Spectra comparison for HRE sunlook test.

As mentioned earlier in this manuscript, there are a few outstanding technical issues needing resolution for system completion and to further optimize this instrument prototype. Regarding spectral tuning, motors of sufficient torque are needed to work in the dewar environment for repositioning etalon plates after cryogenically-induced alignment displacements, and autonomous implementation of the capacitance feedback loop is also desired. For improving spatial imaging and radiometric fidelity, stray light reduction will be pursued; most importantly, the dewar window will be replaced with one that is AR-coated per the original specifications. Additional baffling/optical elements or tilting, as needed, will also be investigated to minimize impact of undesired-reflections-induced spatial/spectral parasitic energy. Subsequent to these h/w enhancements, extensive lab testing/characterization will be repeated, and field deployment(s) and aircraft implementation will be pursued. In parallel, infusion into programs internal and external to NASA will be investigated.

III. Summary

Tropospheric ozone is a high-priority measurement identified in the NASA Science Mission Directorate (SMD) Strategic Enterprise and Science Research Plans. The FPI system (TTSS-FPI) described herein has demonstrated a new measurement capability intended for "direct" geostationary Earth orbit (GEO)-based observation of tropospheric ozone. The concept exploits spatial and temporal benefits obtainable from a GEO-based imaging system, for example, monitoring of regional pollution episodes. The instrument concept and technologies are also applicable to measurement of other important atmospheric trace species. The science justification for pursuing this capability along with the concepts behind the measurement and instrumentation have been described. Also, the approach followed for development and demonstration of this instrument system within NASA's Instrument Incubator Program along with key technical demonstration results have been discussed.

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